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High Altitude Testing of Residential Wood-Fired Combustion Equipment

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16. ABSTRACT

To determine whether emissions from operating a wood stove at high altitude differ from those at low altitude, a high altitude sampling program was conducted which was compared to previously collected low altitude data. The low altitude data used for comparison was that from the study entitled "Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment" prepared by Monsanto Research Corporation (EPA 600/7-80-040, March 1980).

Emission tests were conducted in the identical model stove using the same type of wood with the same moisture content, amount of wood charged, burning rate, air flow rate, and identical sampling intervals and port locations. Particulate emissions, carbon monoxide, and polycyclic organic matter were analyzed and no statistically significant difference in emissions was found. Thus, for a particular type of wood burned, emission tests conducted at any altitude will be applicable to regions of different altitude.

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HIGH ALTITUDE TESTING OF RESIDENTIAL WOOD-FIRED COMBUSTION EQUIPMENT

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This study was undertaken to characterize the particulate, carbon monoxide and polycyclic organic matter emissions from operating a wood stove at high altitudes and to determine if these emissions differ from low altitude emissions. No significant difference was found between high and low altitude emissions of wood stoves.

This information will be of value both to EPA's regulatory program (Office of Air Quality Planning and Standards) and to State Air Quality Planning Boards.

For further information concerning this subject, the Industrial Pollution Control Division should be contacted.

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Abstract

The increase in residential wood burning across the nation has sparked interest in assessing the potential effects of such burning on air quality. In EPA Region VIII, residential wood burning for aesthetic reasons is increasing in the ever-expanding ski areas. Since most ski areas are located in narrow valleys which have a small carrying capacity, the impact of residential wood burning could be significant.

To determine whether emissions from operating a wood stove at high altitude differ from those at low altitude, a high altitude sampling program was conducted which was compared to previously collected low altitude data. The low altitude data used for comparison was that from the study entitled "Preliminary Characterization of Emissions from Wood-Fired Residential Combustion Equipment" prepared by Monsanto Research Corporation (EPA-600/7-80-040, March 1980).

Emission tests were conducted in the identical model stove using the same type of wood with the same moisture content, amount of wood charged, burning rate, air flow rate, and identical sampling intervals and port locations. Particulate emissions, carbon monoxide, and polycyclic organic matter were analyzed and no statistically significant difference in emissions was found. Thus, for a particular type of wood burned, emission tests conducted at any altitude will be applicable to regions of different altitude.

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SECTION 1

INTRODUCTION

Combustion of wood in residential fireplaces and wood-burning stoves is growing in popularity as the cost for other fuel sources increases. The increased use of wood combustion for aesthetic purposes and primary or auxiliary home heating has attacted environmental concern due to increased particulate, carbon monoxide, hydrocarbon, and polycyclic organic material (POM) emissions over other residential fuel types. Widespread residential combustion of wood could produce a dramatically adverse effect on local air quality, and the U.S. Environmental Protection Agency (EPA) is responsible for averting or minimizing such effects.

The potential effects of wood burning on air quality is of particular concern in EPA Region VIII, where residential wood burning is increasing in the ski resort areas and valley communities. One location repeatedly mentioned is Vail, Colorado, a major Rocky Mountain ski resort, where a haze often blankets the valley town on winter evenings and persists through the morning.

A study was conducted by Monsanto Research Corporation (MRC) in 1979 to determine the environmental impact of residential wood combustion equipment [1, 2]. However, the emission testing was conducted at low altitude (1,000 ft above sea level). Since combustion processes and associated emissions can vary at different altitudes, it could not be assumed by EPA Region VIII communities which voluntarily prepare air quality maintenance plans that the existing data from near sea level were applicable to their needs.

In fact, another source testing study [3] conducted in 1977 by PEDCo-Environmental, Inc. in Vail, Colorado, indicated that emission factors from residential wood combustion at high altitude (8,000-9,000 ft) differed from those measured by MRC and others [4, 5, 6] by at least a factor of two.

The objective of this emission testing program was to determine whether emissions from operating a wood stove at high altitude (~7,000 ft) differ from those at low altitude (~1,000 ft), through comparison with the MRC-low altitude data [1]. Accordingly, test conditions duplicated one of the test conditions from the experimental matrix of the previous study, with altitude as the only variable.

The sampling performed by MRC was directed by Richard G. Beer as team leader, with assistance from Daryl G. DeAngelis. The wood stove was tested during the week of November 18-21, 1980. The sample collection methods employed were EPA Methods 1 through 5 and POM sampling by a modified Method 5 train with an XAD-2 resin absorbent trap.

Quality assurance/quality control in the sampling area covered such activities as instrument calibration, using standard or approved sampling methods, chain-of-custody procedures, and protocols for the recording and calculation of data. QA/QC in the analysis area involved using only validated analysis methods, periodic operator QC checking and training, sample QC by the use of splits, reference standards, and spikes, and interlaboratory audits.

SECTION 2

SUMMARY OF RESULTS

Test results for the sampling and analysis of emissions from the nonbaffled wood stove are discussed in this section. Comparison of the test data with the MRC-low altitude study and the PEDCo-Vail source test is made, and overall conclusions and potential implications of the test results are then considered.

Comparison of Test Conditions

The high-altitude emission test program was designed to duplicate one test condition of the experimental matrix of test conditions in the MRC-low altitude test program, namely, burning seasoned oak in a nonbaffled wood stove. The identical model stove was procured and the same wood, surplus from the low altitude program, was burned; the seasoned red oak had been stored outdoors for one year by an MRC test crew member. Table 1 presents a comparison of the proximate and ultimate analyses of the wood burned in the two testing programs. It can be noticed that the wood gained some moisture during its stay outdoors, but that neither moisture value is very high. It was felt by some reviewers of the low altitude test program that the 4% moisture value was exceedingly low and unrepresentative--indicative of indoor storage, of which few stove operators have the luxury. Generally, the differences, other than moisture, between woods are very small.

Other test conditions such as quantity of wood charged, fuel bed configuration, wood burning rate, air flow rate, similarity of visible combustion appearance (flame height), stack gas velocity,

TABLE 1. COMPARISON OF PROXIMATE AND ULTIMATE ANALYSES OF SEASONED RED OAK USED IN HIGH AND LOW ALTITUDE TEST PROGRAMS

Wood composition	High-altitude test wood, as received	Low-altitude test wood, as received
Moisture, %	12.62	4.25
Volatile matter, %	80.65	82.72
Fixed carbon, %	13.25	12.28
Ash, %	0.44	0.75
Sulfur, %	0.02	0.01
Carbon, %	40.43	45.89
Hydrogen[a], %	4.56	6.29
Nitrogen, %	0.12	<0.1
Oxygen[a], %	54.42	46.96
Heating value, Btu/lb	7,319	7,710
Heating value-dry, Btu/lb	8,377	8,060

[a]Includes that from moisture.

average stack temperature, and height of sampling above stove were duplicated as closely as possible. Table 2 summarizes the comparison of test conditions for all runs. The largest deviation from the low altitude test was the ambient temperature in the stove area; this resulted in a lower average stack temperature due to cooler inlet air. Operator manipulation of the burning rate was duplicated well (within 2.5%) considering the coarseness of the available air supply controls. The four high altitude test runs had a burning rate standard deviation which was only ±14% of the mean value. Stack gas flow rate and excess air values compare well between themselves within the high altitude tests and also between the high and low altitude tests.

TABLE 2. COMPARISON SUMMARY OF TEST CONDITIONS FOR WOOD STOVE OPERATED AT HIGH AND LOW ALTITUDES

Test condition	MRC-high altitude runs					MRC-low altitude runs		
	POM 1	POM 2	EPA 5-1	EPA 5-2	Average	POM	EPA 5	Average
Barometric pressure, in. Hg	24.62	24.69	24.65	24.59	24.64	29.4	29.3	29.35
Ambient temperature, °F	45	48	54	50	49	75	71	73
Burning rate, kg/hr	5.64	7.80	6.78	7.44	6.90	8.64	5.49	7.08
Excess air, %	46.6	16.2	41.5	72.4	44.2	25.0	25.0	25.0
Stack gas moisture, %	5.61	12.71	20.43	12.06	12.70	20.24	11.42	15.83
Stack temperature, °F	464	512	516	480	493	713	722	718
Stack flow rate (dry standard), dscfm	33	33	27	27	30	35	32	33.5
Stack flow rate (actual), acfm	74	84	76	67	75.3	98	83	90.5

The air consumption rates presented compare well with published literature values [7]. Table 3 lists typical natural air-ventilation rates (or exchange) rates of houses (due to infiltration around windows and doors), and the air needed for stoves and fireplaces. It can be seen from comparison with Table 2 that the air flow rates during testing (in acfm) are indeed indicative of a large airtight wood heater operated near its upper range or "high" burning rate.

TABLE 3. AIR CONSUMPTION OF WOOD HEATERS AND HOUSE AIR EXCHANGE RATES [7]

Item	Air flow rate	
	lb air/hr	acfm (70°F)
Small closed stove	100-200	22-44
Large closed stove	150-300	33-67
Open stove (e.g., Franklin)	250-500	56-110
Fireplace (with windows and doors closed)	400-1,500	90-330
Typical house ventilation rate	500-2,000	125-500

Closed stoves consume small amounts of air at a rate which is on the order of 10-20% of the natural air-exchange rate of houses, Table 3. A stove which uses a minimum amount of air for a given combustion rate has an advantage. The less air is admitted, the less must be exhausted; hence, the velocity through the stove and stove pipe will be slower. Minimizing the amount of excess combustion air also increases the temperature of the hot gases because excess air dilutes the combustion products, making the mixture cooler. Cooler combustion air will have the same effect, as seen in the stack temperature comparison in Table 2.

Particulate Emissions

Particulate emissions were determined by measuring the mass of material collected by the front half (filterable) of the EPA Method 5 and POM trains. The condensable organic, or back half, emissions were collected only with the EPA Method 5 train. The results, reported in Table 4, indicate that front half filterable particulate emissions rates show good repeatability between runs, with a standard deviation of only ±28% of the mean value emission factor. Thus, replicate runs at a semi-constant burning rate (±14%) will yield repeatable particulate emission factors by EPA Method 5 sampling for a given stove and wood type.

A comparison between the high altitude and low altitude particulate emission results shows that, when the stove operating variables are held constant, there is no statistically significant difference in either filterable particulate or condensable organic emissions. A small increase in filterable particulate emissions for high altitude is observed, but this may be due to the inherent variability of the combustion process (the standard deviation of all six high and low altitude emission factors is only 33% of the mean) or the cooler inlet air during the high altitude test which lowered the combustion zone temperature. Lower combustion temperatures may "quench" combustion in and above the flame zone and increase filterable particulate emissions to a small degree.

Condensable organic emissions were nearly identical between tests and were very close to the value obtained under low altitude testing conditions.

Carbon Monoxide Emissions

Integrated gas sampling during each particulate emission test run with Orsat technique analysis was conducted for CO emissions.

TABLE 4. SUMMARY OF PARTICULATE EMISSION RESULTS FOR HIGH ALTITUDE WOOD STOVE WITH MRC-LOW ALTITUDE RESULT COMPARISON

Test result	MRC-high altitude					MRC-low altitude		
	POM 1	POM 2	EPA 5-1	EPA 5-2	Average	POM	EPA 5	Average
Particulate loading (front), gr/dscf	0.2166	0.2351	0.2359	0.1697	0.2143	0.1986	0.0823	0.1405
Condensable organics (back), gr/dscf	-[a]	-[a]	0.3324	0.3965	0.3645	-[a]	0.2426	0.2426
Particulate loading (total), gr/dscf	-[a]	-[a]	0.5683	0.5662	0.5788	-[a]	0.3249	0.3831
Emission rate (front), lb/hr	0.062	0.067	0.054	0.040	0.056	0.059	0.023	0.041
Emission rate (back), lb/hr	-[a]	-[a]	0.077	0.093	0.085	-[a]	0.066	0.066
Emission rate (total), lb/hr	-[a]	-[a]	0.131	0.133	0.141	-[a]	0.089	0.107
Emission factor (front), g/kg[b]	4.965	3.846	3.687	2.419	3.729	3.1	1.9	2.5
Emission factor (back), g/kg[b]	-[a]	-[a]	5.015	5.645	5.330	-[a]	6.0	6.0
Emission factor (total), g/kg[b]	-[a]	-[a]	8.702	8.064	9.059	-[a]	7.9	8.5

[a]No back-half condensable organics are collected with the POM sampling train.

[b]The kg of wood burned during test not corrected for moisture.

MRC's low altitude program results had shown that CO concentrations in the flue gas can vary by an order of magnitude in only 20 minutes of burn time. Table 5 presents the results and comparison for CO emissions. No significant difference in CO emissions due to altitude can be observed. The low altitude CO emission factor is an average of ten grab samples; the high altitude CO emission factor was developed by integrated gas sampling. Both were analyzed by an Orsat analyzer, and should be equivalent results.

TABLE 5. SUMMARY OF CARBON MONOXIDE EMISSION RESULTS

Test result	MRC-high altitude					MRC-low altitude		
	POM 1	POM 2	EPA 5-1	EPA 5-2	Average	POM	EPA 5	Average
CO concentration, %	2.2	3.0	-[a]	BDL[b]	1.7	2.8[c]	2.8[c]	2.8[c]
CO emission factor, g/kg	273	270	-[a]	0	181	230.5	230.5	230.5

[a]No sample taken.
[b]Below detection limit.
[c]Average of 10 grab samples ranging from 1.8 to 4.2%.

POM Emissions

Polycyclic organic material (POM) emissions were sampled with a modified EPA Method 5 train with XAD-2 absorbent resin followed by solvent extraction and GC/MS analysis. A comparison of results is shown in Table 6 between high and low altitude testing.

The total POM emission factor from the high altitude test was 0.05 g/kg, which was about one-fourth that of the low altitude test. Another noticeable difference was that the high altitude test results had POM compounds identified which tended to be lower in molecular weight. Although unconfirmed, it is felt that the lower combustion zone temperatures of the high altitude test, as indicated by stack gas temperature, suppressed the POM chemical formation mechanisms. This would result in the formation of lower molecular weight POM compounds as well as reduced total POMs

TABLE 6. POM EMISSIONS FROM NONBAFFLED STOVE BURNING SEASONED OAK (g/kg)

POM compounds	Low altitude tests	High altitude tests[a]
Biphenyl	-	0.0016
Methyl-biphenyl	-	0.0020
C_2-alkyl-biphenyl	-	0.0003
Naphthalene	-	0.0127
Methyl naphthalene	-	0.0024
C_2-alkyl naphthalene	-	0.0011
Anthracene/phenanthrene	0.0618	0.0100
Methyl-anthracenes/-phenanthrenes	0.0167	0.0012
C_2-alkyl-anthracenes/-phenanthrenes	0.0045	0.0006
Cyclopenta-anthracenes/-phenanthrenes	0.0030	-
Fluoranthene	0.0208	0.0044
Pyrene	0.0169	0.0026
Methyl-fluoranthrenes/-pyrenes	0.0103	0.0014
C_2-alkyl-fluoranthrenes/-pyrenes	-	0.0006
Benzo(ghi)fluoranthene	0.0047	-
Cyclopenta(ed)pyrene	0.0051	-
Benzo(c)phenanthrene	0.0016	0.0006
Benzo(a)anthracene/chrysene	0.0076	0.0023
Methyl-benzanthracenes-benzophenanthrenes/-chrysenes	0.0062	0.0004
C_2-alkyl-benzathracenes-benzophenanthrenes/-chrysenes	0.0037	-
Benzofluoranthenes	0.0112	0.0021
Benzopyrenes/perylene	0.0084	0.0020
Indenopyrene	-	0.0010
Methyl-benzofluoranthenes/-perylene	-	0.0003
Benzo(ghi)perylene	0.0043	0.0010
Dibenzopyrenes	0.0007	-
Dibenzanthracenes/-phenanthrenes	0.0010	0.0003
TOTAL	0.1885	0.0509

Note: Blanks indicate POM compound not detected.

[a]Average of two runs.

on a mass basis. An even cooler fire should, at some point, result in zero POM emissions since very high temperatures (at least 400-500°C) and a chemically reducing environment are necessary for POM formation from the long-chain molecules present in wood cellulose, lignin, and hemicellulose.

The high altitide POM emission factor was in the same range as several POM emission factors reported for other stove tests [8] in which the burning rate was slightly lower than the MRC-low altitude tests. In addition to POM identification and quantification, twenty-one other high molecular weight organic compounds were identified. Table 7 presents a list of these organic compounds present in wood combustion smoke. Quantitative determination of these compounds was beyond the scope of this study. The compounds found compare well with those identified in the low altitude study.

TABLE 7. ADDITIONAL ORGANIC COMPOUNDS IDENTIFIED IN RESIDENTIAL WOOD COMBUSTION SMOKE, FT. COLLINS, COLORADO

Organic compounds
Benzaldehyde
Phenol
Cresol
Ethyl phenol
C_3-alkyl-phenol
C_4-alkyl-phenol
Phenyl diphenylcarboxylate
Methyl bicycloheptene
Diethyl phthalate
Dioctyl phthalate
Diallyl terephthalate
Tetrahydronaphthalene
C_5-alkyl phenol
Dibenzofuran
Dimethylbenzofuran
Propoxyphenol
Tricresyl phosphate
Vanillin
Vanillic acid
Fluorenone
Naphthol

Comparison With PEDCo-Vail Results

A comparison between MRC's high altitude and low altitude emission tests leads to the conclusion that, when the operating variables are held constant, there is no statistically significant difference in particulate or CO emissions. Tables 8 and 9 present comparison summaries of the MRC results with the PEDCo-Vail wood stove results for test conditions and emission results, respectively. So why, then, are the PEDCo-Vail particulate emission test results three times as high? It should be noticed that the CO emission factors between the three tests are similar.

TABLE 8. COMPARISON SUMMARY OF EMISSION TEST CONDITIONS FOR THREE WOOD STOVE TESTS

Description (68°F)	Units	MRC-high altitude	MRC-low altitude	PEDCo-Vail
Barometric pressure	in. Hg	24.64	29.35	21.58
Ambient temperature	°F	49	73	50
Wood type		seasoned oak	seasoned oak	seasoned pine
Burning rate	kg/hr	6.9	7.1	6.2[a]
Excess air	%	44.2	25.0	47.1
Stack temperature	°F	493	718	415
Stack flow rate (dry standard)	dscfm	30.0	33.5	63.1
Stack flow rate (actual)	acfm	75.3	90.5	152

[a]Estimated.

TABLE 9. COMPARISON SUMMARY OF WOOD STOVE EMISSION RESULTS

Description (68°F)	Units	MRC-high altitude	MRC-low altitude	PEDCo-Vail
Particulate loading (front)	gr/dscf	0.2143	0.1405	0.1408
Particulate loading (back)	gr/dscf	0.3645	0.2426	0.5756
Particulate loading (total)	gr/dscf	0.5788	0.3249	0.7164
Emission rate (front)	lb/hr	0.056	0.041	0.076
Emission rate (back)	lb/hr	0.085	0.066	0.311
Emission rate (total)	lb/hr	0.141	0.107	0.387
Emission factor (front)	g/kg	3.73	2.50	5.56
Emission factor (back)	g/kg	5.33	6.00	22.74
Emission Factor (total)	g/kg	9.06	8.50	28.30
CO emission factor	g/kg	181	230.5	219

A major deficiency of the PEDCo-Vail study was the absence of gravimetric determination of the wood weight remaining in the stove for burning rate and, ultimately, emission factor calculations. The subjective estimation of wood weight in the firebox based on the apparent volume of wood will tend to bias the error in weight estimate toward the low side which, then, inflates the emission factor. It is safer to compare only pollutant loadings and emission rates.

The filterable particulate stack gas concentration (0.1408 gr/dscf) for PEDCo's test was in the same range as either MRC study. PEDCo's stove, however, had a much higher flue gas flow rate (152 acfm), indicative of a nonairtight stove as shown in Table 3. The higher flow rate resulted in a slightly larger emission rate on a lb/hr basis. The higher emission rate could be due entirely to the reduced burning rate, since Butcher [9] has shown (using a hi-volume stack sampling system) that particulate emissions are inversely proportional to burning rate.

The PEDCo test had much greater condensable organic emissions--0.311 lb/hr vs 0.085 lb/hr for MRC's study. This was due probably to two main reasons: PEDCo burned dry pine and burned it at a lower temperature. The use of pine, a more resinous wood, can have an increased effect on emissions, especially condensable organics, over the use of a hardwood such as oak. MRC's low altitude study found that condensable organic emissions doubled (to 10-12 g/kg) when burning green pine but the results did not indicate the same for dry pine. However, the MRC low altitude study had greater stack gas temperatures (700°F vs 415°F) which indicate a higher stove combustion zone temperature. In the PEDCo-Vail stove test, the stack temperature was measured at the stove exit rather than in the flue. The stove inlet air temperature was unusually low (similar to the MRC high altitude tests) at 50°F. Thus, it was likely that the lower combustion zone temperature created more unburned volatiles which were "quenched"

by the excess cool inlet air rising above the combustion zone. Also, because of the weight estimates for unburned wood charge, it is likely that PEDCo's reported burning rate was lower and the emission factor became inflated.

Carbon monoxide emissions appear to be within the range of both MRC emission test results. PEDCo's carbon monoxide sampling technique was by EPA Method 3 integrated gas bag collection, same as the MRC high altitude tests, followed by Orsat analysis. Comparison of PEDCo's CO results with other tests they conducted on fireplace emissions showed that stove CO emissions (in g/kg) were 2-5 times higher than fireplace CO emissions, a result which MRC observed in the low altitude testing program.

Data from other wood stove sampling programs [8, 10] indicate that updraft and sidedraft type stoves typically have CO emission factors in the 150-400 g/kg range. The degree of incomplete combustion at high burning rates in these types of stoves appears to remain fairly constant over the period of at least a whole charge of wood burned, although instantaneous CO readings can fluctuate wildly. Allen [8] has shown that at a high burning rate CO and unburned hydrocarbon emissions (measured as THC with a GC/FID) correlate well; the THC/CO emission ratio is roughly 1:5.

SECTION 3

STOVE DESCRIPTION AND TESTING OPERATION

The woodburning stove tested was the identical model stove to one used in the MRC-low altitude study. This nonbaffled stove is an airtight, boiler plate construction, radiant heater with an updraft combustion-air flow pattern. The combustion zone dimensions are approximately 0.61 m high, 0.4 m wide, and 0.72 m long. Two adjustable air inlets (primary air) are located on the door of the stove. The unit, shown in Figure 1, weighs approximately 160 kg (350 lb) and is lined with firebrick.

The stove and associated flue pipe were mounted on a single-beam mechanical scale to provide weight determination for wood burning rate. Weight readings were taken at 10-minute intervals, whenever additional wood was charged to the stove, and at the start-up and shut-down of the sampling trains.

As a precaution against sampling probes affecting weight readings during thermal expansion and contraction of the stack, the sampling trains were positioned so that the probes did not contact the stack. Furnace tape was used to seal around the probes to prevent ambient air infiltration to the stack. In this way, any upward or downward movement of the stack caused the tape to flex rather than exert a force against the stack and influence weight readings. Weight readings taken with and without the trains in place showed no measureable influence on the weight determination in this test program.

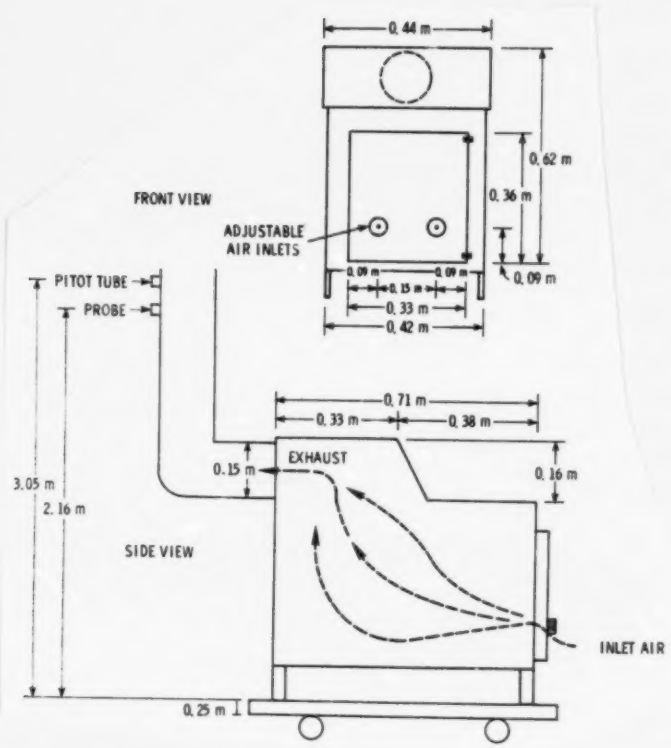

Figure 1. Nonbaffled airtight stove showing generalized combustion-air flow pattern.

The emission testing took place at the Colorado State University Forest Service maintenance shop in an unheated sheet metal building. Ambient temperature inside was about 45-54°F. The total stack height from ground level to roof was about 30 ft, with 4 ft of stove pipe chimney above the roof.

The height of the sample pulling position in the stack duplicated the MRC-low altitude position at a height of 2.2 m from the stove base.

Two charges of wood were allowed to burn before testing began to let the equipment reach thermal equilibrium and to establish a bed of coals in the stove. Initial startup of a fire, although possibly generating significant emissions, was not studied.

Combustion conditions were maintained in the stove by manipulation of the air inlet vents until combustion was not excessive (flames reaching into the exhaust pipe) but also not smoldering (no visible flame present). This manipulation consisted of 1.5 to 2 turns on the dual air vents to maintain a wood burning rate of 6.0 kg/hr to 8.4 kg/hr. No other disturbances to the fuel bed took place except for an occasional manipulation of the fuel bed to prevent smothering the fire, and this was kept to a minimum. Ash or combustion residue was not removed during testing.

Integrated sampling, such as the EPA-5 and POM train, spanned at least two charges of wood. Sampling equipment operation was maintained during the charging of a load of wood to the stove. The first test run (EPA 5-1) was started at the beginning of a wood charge and the filter plugged in about 10 minutes. By the time the filter was changed and filter holder oven brought back up to temperature, the wood charge had been half burned. The first run then continued through two more charges of wood, ending just after the third wood charge. Accordingly, this run had the largest stack gas moisture (see Table 2), since the first stage of wood combustion is moisture volatilization (drying). The front-half filter from the first 10 minutes of run EPA 5-1 had a deep black color, and the filter from the remainder of the run was a dark gray color. The back half filter loading appeared similar to the MRC-low altitude back half filters, a yellow color.

For the other three test runs (POM-1, EPA 5-2, and POM-2), sampling was initiated about halfway through a wood charged burn, and continued through another addition of wood to the stove.

Integrated gas sampling for CO, CO_2, and O_2 was conducted throughout each Method 5 or POM run by Tedlar bag collection. During the filter change of run EPA 5-1, the diaphragm-type pump used to collect the gas sample was not switched back on and no EPA Method 3 sample was collected.

SECTION 4

SAMPLING AND ANALYTICAL PROCEDURES

The nonbaffled, updraft wood burning stove was sampled for particulate matter, integrated gas analysis, polycyclic organic material (POM), and fuel analysis. The following describes the methods used.

Sampling Procedures

Exhaust gas sampling was conducted in accordance with procedures outlined in the Environmental Protection Agency's Standards of Performance for New Stationary Sources, Methods 1 through 5, (Federal Register, 40CFR60, December 23, 1971, as amended through August 18, 1977).

Rather than traverse sampling point-by-point, exhaust gas velocity and temperature were preliminarily measured at a single point in the center of the stack. Flat velocity profiles have been demonstrated on solid-fuel residential heating devices [11]. Velocity pressure was obtained using an S-type pitot tube and a 0 to 2-in. water hook gage manometer. Temperatures were measured with a Type K thermocouple attached to the pitot tube. Stack gas moisture content was determined using the volumetric condensate procedure.

Particulate Emissions

Two particulate runs, one 80 minutes and the other 67 minutes in duration, were conducted at the wood stove stack 2.2 m above the

scales under the stove. Exhaust gases were withdrawn isokinetically at the center point of the stack. Because of the cyclic nature of the combustion process, the temperature at the point of sampling varied by 275°F. Rather than use average stack temperature to determine the K factor [12], the temperature at each reading (5-min intervals) was used to determine a new K factor.

The K factor is a proportionality factor relating stack velocity measurement pressure differential and gas meter orifice pressure differential to obtain isokinetic sampling. Figure 2 is a reproduction of a graph employed in the field for K factor determination.

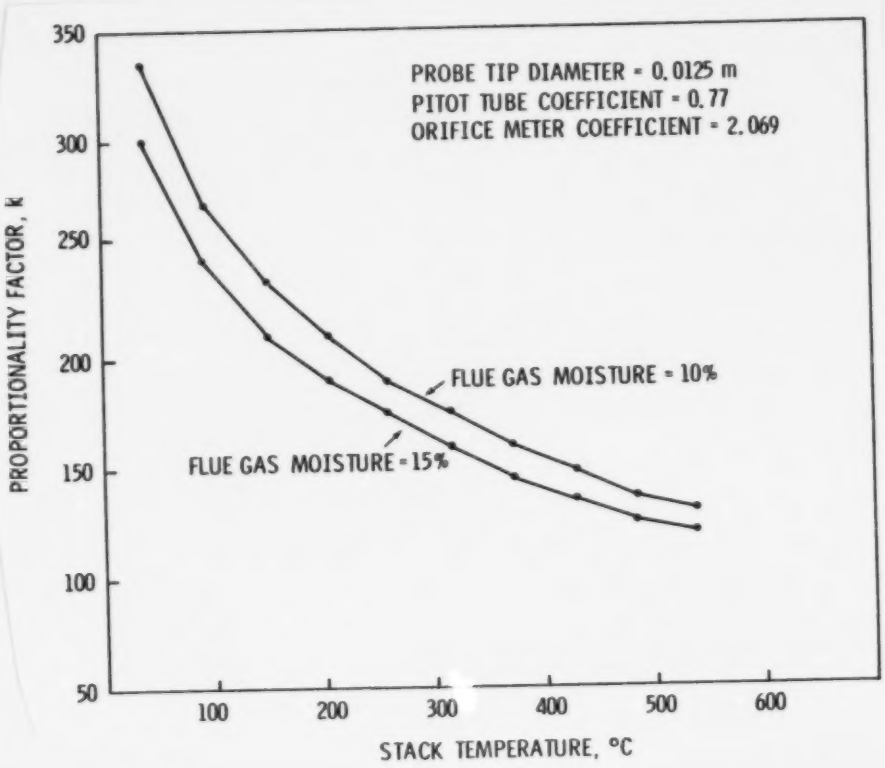

Figure 2. Example of EPA Method 5 train proportionality (K) versus stack temperature for several flue gas moisture contents.

Sampling for particulates was performed using the method outlined in the Federal Register, Method 5, "Determination of Particulate Emissions from Stationary Sources." The sampling train consisted of a sharp, tapered stainless steel nozzle; a 2-ft heated glass-lined probe; a heated 3-inch Gelman spectrograde glass-fiber filter; followed by the impinger assembly which consisted of one modified and one standard Greenburg-Smith impinger, each containing 100 mL of distilled water, an empty modified Greenburg-Smith impinger serving as a dry trap, a back-up 3-in. glass-fiber filter, and a modified Greenburg-Smith impinger containing about 300 g of silica gel; a leakless pump with vacuum gage; a calibrated dry-gas meter equipped with inlet and outlet thermocouples; and a calibrated orifice-type flow meter which was connected to a 0 to 10-in. range inclined manometer. All of the sampling train glassware was connected by ground glass joints, sealed with stopcock grease, and clamped to prevent leakage. Figure 3 illustrates the sampling train schematic.

Prior to and upon completion of each sample run, the entire sampling train was checked for leaks in accordance with the requirement that the leak rate shall not exceed 0.02 cubic feet per minute at 15 inches of mercury vacuum before the run and the post leak rate at the highest vacuum incurred during the run. At the completion of each sample run and the post leak check, the sampling train was transferred to a relatively dust-free area for sample transfer.

The 3-in. glass-fiber filters were transferred to their original petri dishes. The nozzle, probe, and front half of the glass filter holder were thoroughly rinsed and brushed three times with acetone. The rinsings were collected in glass sample bottles with Teflon-lined caps. The condensate was measured and the volume increase recorded. The water was then discarded.

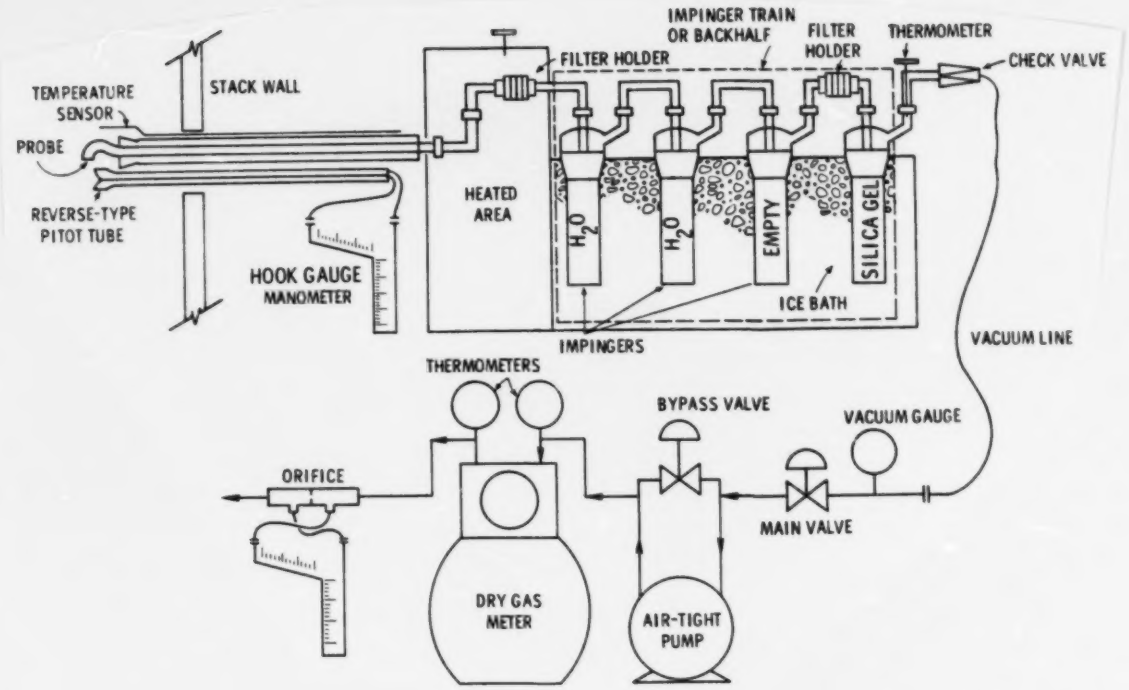

Figure 3. Schematic of EPA Method 5 sampling train with back-up filter for particulate and condensable organic material collection.

The silica gel impinger was weighed and the weight gain included as condensate. Therefore, with each particulate run, three sample fractions had been collected for analysis:

(1) front 3-in. glass-fiber filter; and,
(2) acetone rinsings of nozzle, probe, and front half of the filter holder assembly,
(3) back 3-in. glass-fiber filter.

In the laboratory, each fraction was dried and equilibrated in a temperature and humidity controlled room and weighed on an analytical balance to within 0.1 milligram. The weights are tabulated in Appendix B.

Concurrently with each particulate run, burning rate data were recorded by MRC personnel. These data were used to determine particulate emission rates relative to the burning rate and are presented in Appendix A.

Integrated Gas Analysis

Exhaust gas composition was performed using the method outlined in the Federal Register, Method 3, "Gas Analysis for Carbon Dioxide, Oxygen, Excess Air, and Dry Molecular Weight." This method also analyzes for carbon monoxide concentration.

Simultaneously with each particulate sample, exhaust gas samples were taken for composition analysis using the Orsat method. The exhaust gas was drawn by a pump through a probe, tubing, and condenser to a 2-liter Tedlar gas bag, gradually filling the bag at a controlled flow rate. At the end of each sample run, an aliquot of the gas collected in the bag was passed through an Orsat apparatus which measured the concentrations of carbon dioxide, oxygen, and carbon monoxide by the standard Orsat method. Volume decreases were noted after each gaseous component was selectively absorbed from the sample. These results were used to calculate the specific gravity of the exhaust gas relative to dry air.

POM Emissions

Two POM runs, one 62 minutes and the other 65 minutes long, were conducted at the same sampling point in the wood stove stack as the EPA Method 5 runs.

Sampling for POM emissions was performed using a modified EPA Method 5 train which is operated using the method outlined above for EPA Method 5. The sampling train consists of a sharp, tapered stainless steel nozzle; a 2-ft heated glass-lined probe;

a heated 3-in. Gelman spectrograde glass fiber filter; followed by an impinger and resin trap assembly which consisted of one modified Greenburg-Smith impinger immersed in the ice bath to function as a cooler trap to cool the gas to about 20°C before introduction to the absorbent resin, a glass cartridge containing about 30 g of Rohm and Haas XAD-2 porous polymer absorbent resin (a styrene-divinylbenzene polymer) held in place with glass wool at both ends, one standard and one modified Greenburg-Smith impinger, each containing 100 mL of distilled water, and a modified Greenburg-Smith impinger containing about 300 g of silica gel; a leakless pump with vacuum gage; a calibrated dry-gas meter equipped with inlet and outlet thermocouples; and a calibrated orifice-type flowmeter which was connected to a 0 to 10-in. range inclined manometer. All of the sampling train glassware was connected by ground glass joints, sealed with a minimal amount of spectro-vac-2 stopcock grease, and clamped to prevent leakage.

At the completion of a sampling run, the resin trap was removed and capped. The entire train, from probe tip to filter holder, was cleaned with methylene chloride and the rinse sample was bottled in amber glass. Cooler trap contents were measured, and the liquid and methylene chloride rinse were poured into an amber bottle. Contents of the water impinger were also measured in order to determine the quantity of condensed water. The silica gel impinger contents were weighed, and the material discarded. All samples were stored in a cooler and delivered to MRC's Dayton Laboratory on ice.

This system also determined particulate emissions in accordance with the standard EPA Method 5 procedure since the front half of the train remained unchanged, the only exception being a methylene chloride rinse instead of acetone. Figure 4 shows the sampling train components and sample recovery procedure for the modification.

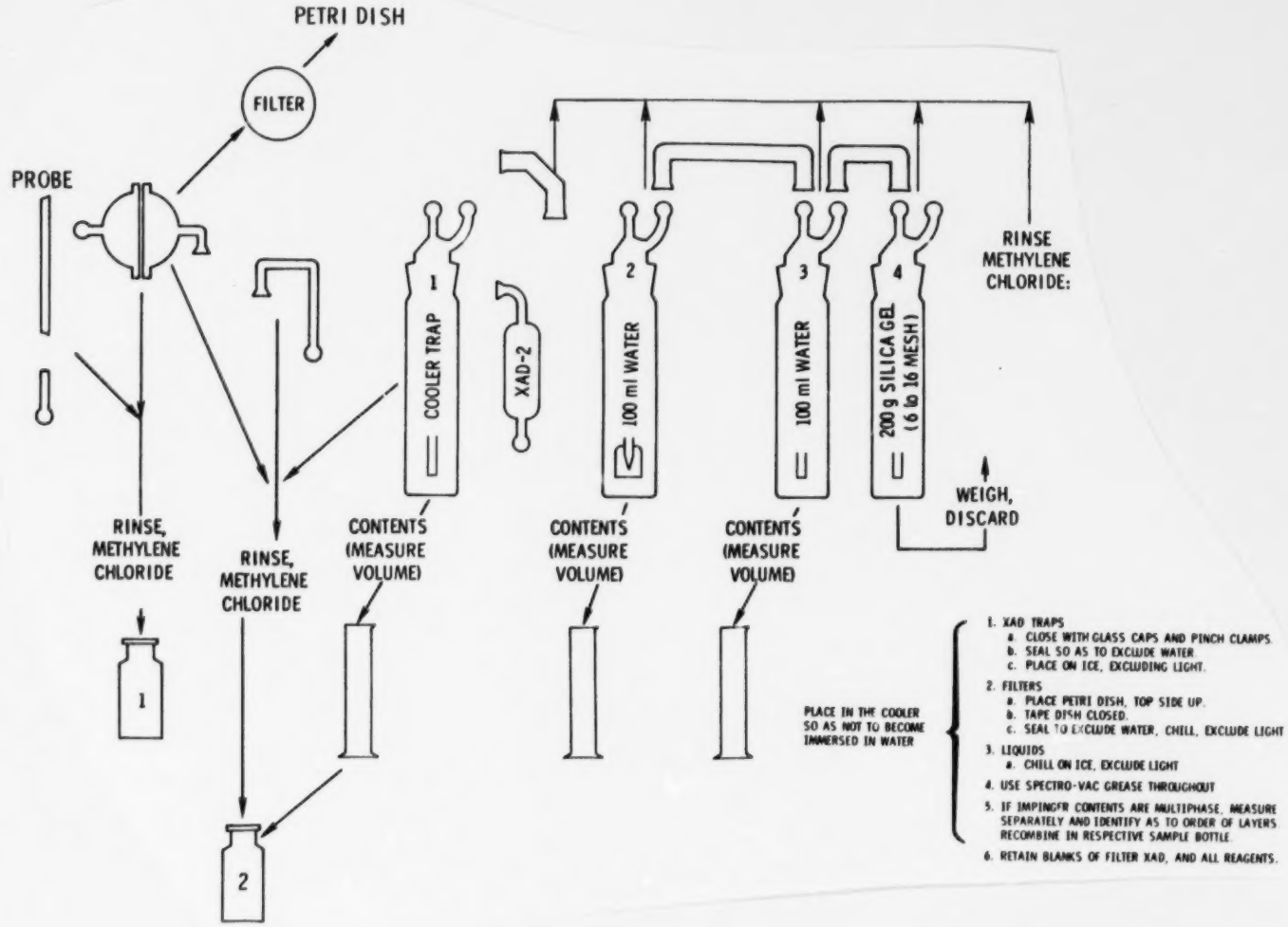
PETRI DISH
FILTER
PROBE
1
COOLER TRAP
XAD-2
2
100 ml WATER
3
100 ml WATER
4
200 g SILICA GEL (6 to 16 MESH)
RINSE METHYLENE CHLORIDE:
WEIGH, DISCARD
RINSE, METHYLENE CHLORIDE
RINSE, METHYLENE CHLORIDE
CONTENTS (MEASURE VOLUME)
CONTENTS (MEASURE VOLUME)
CONTENTS (MEASURE VOLUME)
1
2
PLACE IN THE COOLER SO AS NOT TO BECOME IMMERSED IN WATER
1. XAD TRAPS
a. CLOSE WITH GLASS CAPS AND PINCH CLAMPS.
b. SEAL SO AS TO EXCLUDE WATER.
c. PLACE ON ICE, EXCLUDING LIGHT.
2. FILTERS
a. PLACE PETRI DISH, TOP SIDE UP.
b. TAPE DISH CLOSED.
c. SEAL TO EXCLUDE WATER, CHILL, EXCLUDE LIGHT
3. LIQUIDS
a. CHILL ON ICE, EXCLUDE LIGHT
4. USE SPECTRO-VAC GREASE THROUGHOUT
5. IF IMPINGER CONTENTS ARE MULTIPHASE, MEASURE SEPARATELY AND IDENTIFY AS TO ORDER OF LAYERS. RECOMBINE IN RESPECTIVE SAMPLE BOTTLE.
6. RETAIN BLANKS OF FILTER XAD, AND ALL REAGENTS.

Figure 4. Schematic of POM train components and sample recovery.

Flue Gas Velocity Measurement

Because flue gas velocities were generally below 10 ft/s and often below 5 ft/s, it was necessary to employ a velocity head (ΔP_s) measuring system more sensitive to low velocities than the "S" type pitot tube with conventional manometer, which loses accuracy rapidly at the low end of the measurement scale.

Velocities for the MRC-low altitude program were determined by employing an "S" type pitot tube and a 6-ft tall Meriam micromanometer (Model 34FB2) with a range of 0 to 37.4 mm Hg. This manometer uses a scale of much greater expansion than the typical field micromanometer and employed a vernier adjustment to obtain a velocity reading in inches of water. The manometer was extremely sensitive to velocity changes at low flow rates and could be accurately read down to 1.87×10^{-4} mm Hg, although many times readings had to be taken at the lowest end of the scale. Any instantaneous fluctuations in pressure head made readings difficult to take.

In this sampling program, an improvement in velocity measurement was made by using a Dwyer Microtector® which combines the principles of the hook gage type manometer and solid state integrated circuit electronics. Accuracy and repeatability can be achieved within ±0.00025 in H_2O (4.7×10^{-4} mm Hg) throughout its 0 to 2 in H_2O range. The improvement lies in the technique of obtaining an instantaneous measurement from a fluctuating pressure head source.

The principle of operation is that the pressure to be measured is applied to the manometer fluid which is displaced in each leg of the manometer by an amount equal to one-half the applied pressure. A micrometer mounted hook is then lowered until it contacts the manometer gage fluid, as depicted in Figure 5. The instant of

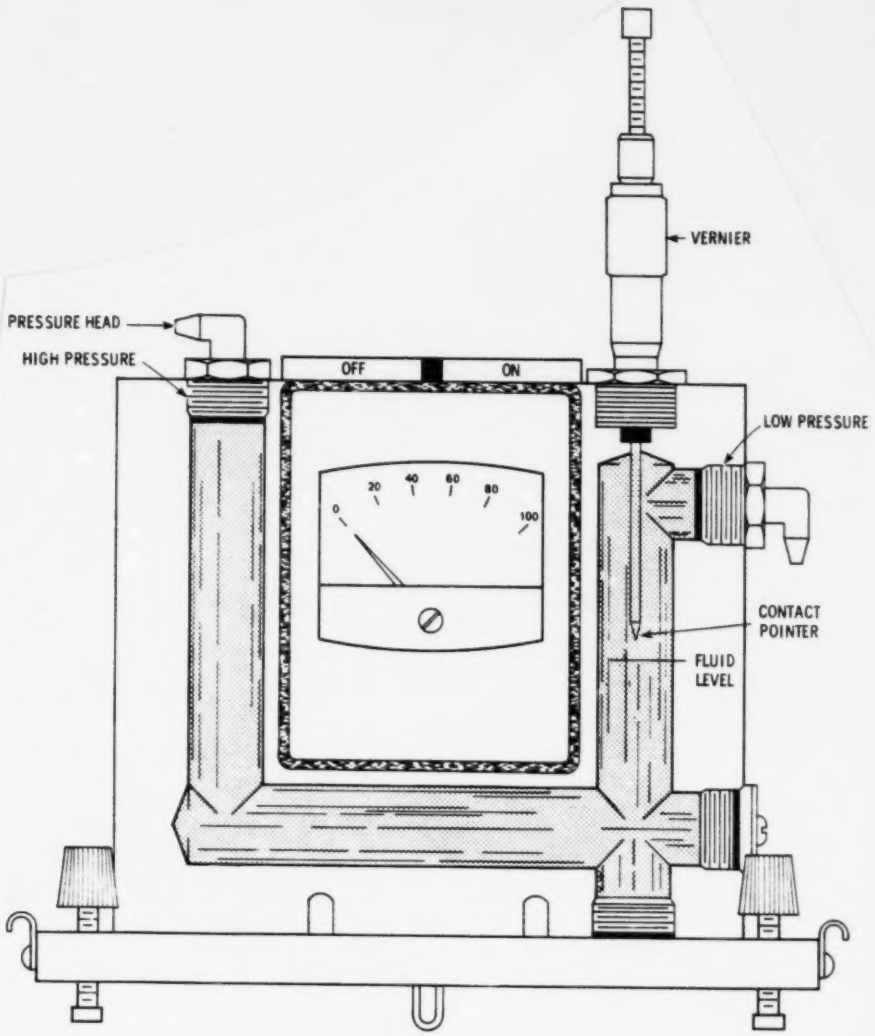

Figure 5. Hook gage manometer used for low flow velocity head measurement.

contact is detected by completion of a low power a.c. circuit, which activates a bridge rectifier providing a signal for indication on a 0 to 50 microamp d.c. microammeter. On indication of contact, the operator stops lowering the hook and reads the Vernier micrometer which indicates one-half the applied pressure.

Analytical Procedures

POM Analysis

Before POM analysis began, all sample fractions from each POM train run were combined. These included: the filters and XAD-2 resin; probe wash, filter holder wash, back half filter holder wash, and cooler trap contents and wash. The washes were extracted with methylene chloride (CH_2Cl_2), separated, and the methylene chloride added to the soxhlet extract after extraction of the solids. The filters and resin were soxhlet extracted separately with CH_2Cl_2 for 16 hr. Figure 6 illustrates the flow diagram of the analytical protocol.

After combining the extracts, the sample was solvent reduced to 1 mL, then exchanged into hexane. The extract was then separated on a silica column using hexane, methylene chloride, and methanol to elute the column. The methylene chloride fraction was saved for POM analysis, after further reduction to 1 mL.

The same procedure was used for the other POM train run and a blank run consisting of a blank filter and XAD-2 resin.

The extracts were analyzed by injection into an HP-5985 gas chromatography/mass spectrometry (GC/MS) system with the following conditions:

- 25 m x 0.15 mm (ID) fused silica column
- Wall-coated-open-tubular, coated with SP2100 methyl silicone fluid
- Initial temperature 50°C

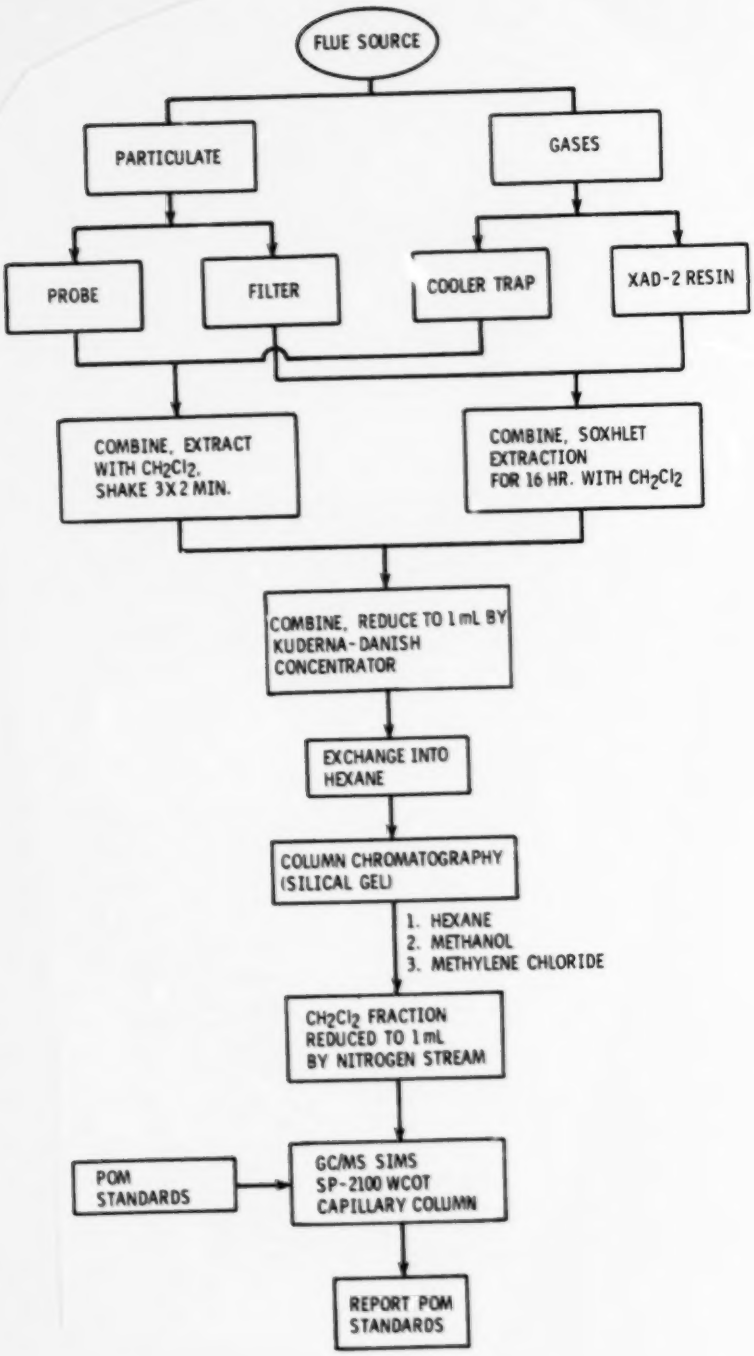

Figure 6. Schematic diagram of POM analysis protocol.

- Held at initial temperature for 1 min
- Heating rate of 8°C/min
- Final temperature of 280°C
- Splitless injections
- He carrier gas at 40 mL/min

The resultant peaks were identified by comparison with their mass spectra to known mass spectra, and the POMs were quantified by running standards at known concentrations under identical conditions. The standard compounds used were: biphenyl, perylene, benzo(ghi)perylene, chrysene, pyrene, phenanthrene, and naphthalene.

Fuel

Analysis of the seasoned red oak sample saved from the emission test was performed using ASTM D3176 for determination of the ultimate analysis (carbon, hydrogen, nitrogen, sulfur, oxygen, and ash), ASTM D3173 for moisture content, ASTM D3172 for proximate analysis (volatile matter and fixed carbon), and ASTM D2015 for Btu content.

Quality Assurance/Quality Control

Results of quality control tests are furnished with the analytical data sheets provided in Appendix B.

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16 DECEMBER 1980

FT. COLLINS WOOD STOVE
PARTICULATE SAMPLING

ABBR	DESCRIPTION (68 DEG F)	UNITS	POM1	POM2	EPA1	EPA2
TT	DURATION OF RUN	MINUTES	61.9	65.0	80.0	67.0
PB	BAROMETRIC PRESSURE	IN HG	24.62	24.69	24.65	24.59
DELH	AVG ORIFICE PRESS DROP	IN H2O	0.208	0.256	0.186	0.172
VA	VOL DRY GAS(METER CON)	DCF	16.652	18.182	19.377	15.332
TM	AVG GAS METER TEMP	DEG F	61.7	56.1	69.0	58.2
VMSTD	VOL DRY GAS (STD COND)	DSCF	15.88	15.36	15.94	12.85
VW	TOTAL H2O COLLECTED	ML	17.5	47.5	86.9	37.4
VWG	VOL H2O VAPOR(STD CON)	SCF	0.824	2.237	4.093	1.762
PCNTM	PERCENT MOISTURE BY VOL		5.61	12.71	20.43	12.06
MD	MOLE FRACTION DRY GAS		0.944	0.873	0.796	0.879
CO2	PERCENT CO2		10.2	14.6	11.9	10.8
O2	PERCENT O2		7.8	4.4	7.0	8.9
N2	PERCENT N2		79.8	79.0	79.4	80.3
MWD	MOL WT OF DRY GAS		29.9	30.8	30.2	30.1
MW	MOL WT OF STACK GAS		29.3	29.2	27.7	28.6
DELP	AVG STACK VELOCITY HEAD	IN H2O	0.007	0.009	0.007	0.006
CP	PITOT COEFFICIENT		0.770	0.770	0.770	0.770
TS	STACK TEMPERATURE	DEG F	464.	512.	516.	480.
PM	STACK PRESSURE(STATIC)	IN H2O	0.00	0.00	0.00	0.00
PS	STACK PRESSURE (ABS)	IN HG	24.62	24.69	24.65	24.59
VS	AVG STACK GAS VELOCITY	FPM	379.	430.	385.	343.
DS	STACK DIAMETER	INCHES	6.00	6.00	6.00	6.00
AS	STACK AREA	SQ IN	28.3	28.3	28.3	28.3
QS	STACK FLOW RT(DRY STD)	DSCFM	33.	33.	27.	27.
QA	STACK FLOW RT(ACTUAL)	ACFM	74.	84.	76.	67.
DN	PROBE TIP DIAMETER	INCHES	0.493	0.493	0.493	0.493
PCTI	PERCENT ISOKINETIC		100.6	106.0	110.2	103.9
MF	PARTICULATE (FRONT)	MG	195.20	234.60	244.20	141.60
MT	PARTICULATE (TOTAL)	MG	0.00	0.00	588.36	472.34
CAN	PARTICULATE (FRONT)	GR/DSCF	0.2166	0.2351	0.2359	0.1697
CAO	PARTICULATE (TOTAL)	GR/DSCF	0.0000	0.0000	0.5683	0.5662
CAI	PARTICULATE (FRONT)	GR/ACF	0.0961	0.0921	0.0836	0.0689
CAU	PARTICULATE (TOTAL)	GR/ACF	0.0000	0.0000	0.2015	0.2298
CAW	PARTICULATE (FRONT)	LB/HR	0.062	0.067	0.054	0.040
CAX	PARTICULATE (TOTAL)	LB/HR	0.000	0.000	0.131	0.133

APPENDIX A

FIELD DATA SHEETS

The handwritten data sheets referenced in this report have not been included because their duplicating quality is poor.

If this information is of interest, write or telephone the following:

Victor F. Jelen, Chief
Food and Wood Products Branch
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
26 W. St. Clair Street
Cincinnati, OH 45268
(513) 684-4227

APPENDIX B

ANALYTICAL DATA SHEETS

The handwritten data sheets referenced in this report have not been included because their duplicating quality is poor.

If this information is of interest, write or telephone the following:

Victor F. Jelen, Chief
Food and Wood Products Branch
Industrial Pollution Control Division
Industrial Environmental Research Laboratory
26 W. St. Clair Street
Cincinnati, OH 45268
(513) 684-4227

APPENDIX C

EQUIPMENT CALIBRATION

CALIBRATIONS

GENERAL

All measuring equipment MRC uses is initially calibrated before use. Equipment which can change calibration is both checked upon return from each field use and is also periodically recalibrated in full. When an instrument is found out of calibration, it is so noted in the report and appropriate adjustments are made to the final results. The equipment is then repaired and recalibrated or retired as needed. Specific equipment is handled as follows:

PITOT TUBE

All pitot tubes used by MRC, whether separate or attached to a sampling probe, are constructed in-house. Prior to their initial usage, they are in a wind tunnel against a standard pitot tube. As long as it is not damaged, it should not change its calibration. The recalibration schedule for pitot tubes is related to the physical condition and usage of the pitot tube, not a fixed time schedule. Each pitot tube is inspected upon return to the laboratory from each field use.

DRY GAS METER AND ORIFICE METER

All MRC meter boxes are calibrated upon purchase and at lease once every six months against a primary wet test meter according to their usage history. Basic procedures are outlined in the EPA Publication No. APTD-0576. The only differences are in the choice of flow rates used and the volumes metered at each flow rate. After each field use, quick checks are performed to insure ΔH at changes of less than 5%. These checks compare the orifice against the dry gas meter. If greater than 5% changes occur, recalibration and repaid are instructed.

NOZZLES

Each nozzle is constructed in-house and calibrated, and thereafter whenever it becomes apparent that the nozzle has become damaged. Each nozzle is inspected upon return to laboratory from each field use. The diameter is measured by a plug gauge with the high and low readings differing by no more than 0.004 in. as a tolerance.

TEMPERATURE MEASURING INSTRUMENTS

After each field use, the thermocouples are calibrated against an ASTM precision mercury-in-glass thermometer across a wide range of temperatures.

MONSANTO COMPANY

Nº 1921225

SUBJECT: Calibration of Consol # 3

JOB NO.	PREPARED BY (SIGNATURE)	DATE
13-022-760.43-101.1232	Dennis J. Gault	1-7-80

29.08
- .116
- .015

DRY GAS METER AND ORIFICE SYSTEM CALIBRATION

DATE 1-6-80 OPERATOR D. Gault CONSOLE NUMBER 3

* Orifice Manometer Setting In. H_2O ΔH	Minimum Volume of Gas ft^3	WET TEST METER GAS VOLUMES AND TEMPERATURES						DRY TEST METER GAS VOLUMES AND TEMPERATURES						Total Test Time Minutes θ	Barometer Reading, Inches Hg P_b
		Initial		Final				Initial	Final						
		ft^3 V_{w_i}	Temp. °F T_{w_i}	ft^3 V_{w_f}	Temp. °F T_{w_f}	Net Volume ft^3 V_w	Avg. Temp. °F T_w	ft^3 V_{d_i}	ft^3 V_{d_o}	Temp. °F T_{d_i}	Temp. °F T_{d_o}	Net Volume ft^3 V_d	Avg. Temp. °F T_d		
0.5	5	1.298	66	6.861	66	5.563	66	616.718	622.301	70.5	73.5	5.583	72	14.74	28.95
0.75	5	6.861	66	12.815	66	5.954	66	622.301	628.272	73.0	73.0	5.991	73	12.99	28.95
1.00	5	71.315	66	77.000	66	5.185	66	628.292	633.50	69.5	71.5	5.208	70.5	9.82	28.95
1.50	10	77.000	66	87.45	66	10.45	66	633.500	644.052	72.5	75.0	10.552	73.5	16.32	29.00
2.00	10	87.69	66	98.00	66	10.31	66	644.376	654.679	70.5	73.5	10.303	72	13.93	29.00
2.50	10	98.48	66	109.00	66	10.52	66	655.183	665.801	70.0	73.5	10.618	71.75	12.67	29.00

Note: Electrical check, Front + Back unit leak check completed adjusted gamma prior to calibration

* Check at least every 2 minutes and adjust if needed.

CALCULATIONS

$$\gamma = \frac{(V_w)(P_b)(T_d + 460)}{(V_d)(P + \frac{\Delta H}{13.6})(T_w + 460)} \qquad \Delta H@ = \frac{0.0317\ (\Delta H)}{(P_b)(T_d + 460)} \left[\frac{(T_w + 460)\ \theta}{(V_w)}\right]^2$$

Calc. By: D. Gault
Checked By: J. Yeager
Date: 1-7-80

ΔH	GAMMA CALCULATIONS	γ	$\Delta H@$ CALCULATIONS	$\Delta H@$
0.5	$\frac{(5.563)(28.95)(72 + 460)}{(5.583)(28.95 + \frac{0.5}{13.6})(66 + 460)}$	1.007	$\frac{0.0317\ (0.5)}{(28.95)(72 + 460)}\left[\frac{(66 + 460)(14.74)}{(5.563)}\right]^2$	1.799
0.75	$\frac{(5.954)(28.95)(73 + 460)}{(5.991)(28.95 + \frac{.75}{13.6})(66 + 460)}$	1.005	$\frac{0.0317\ (.75)}{(28.95)(73 + 460)}\left[\frac{(66 + 460)(12.99)}{(5.954)}\right]^2$	2.029
1.00	$\frac{(5.185)(28.95)(70.5 + 460)}{(5.208)(28.95 + \frac{1.00}{13.6})(66 + 460)}$	1.001	$\frac{0.0317\ (1.00)}{(28.95)(70.5 + 460)}\left[\frac{(66 + 460)(9.82)}{(5.185)}\right]^2$	2.048
1.50	$\frac{(10.45)(29.00)(73.5 + 460)}{(10.552)(29.00 + \frac{1.5}{13.6})(66 + 460)}$	1.001	$\frac{0.0317\ (1.5)}{(29.00)(73.5 + 460)}\left[\frac{(66 + 460)(16.32)}{(10.45)}\right]^2$	2.074
2.00	$\frac{(10.31)(29.00)(72 + 460)}{(10.303)(29.00 + \frac{2.0}{13.6})(66 + 460)}$	1.007	$\frac{0.0317\ (2.00)}{(29.00)(72 + 460)}\left[\frac{(66 + 460)(13.93)}{(10.31)}\right]^2$	2.076
2.50	$\frac{(10.52)(29.00)(71.75 + 460)}{(10.618)(29.00 + \frac{2.5}{13.6})(66 + 460)}$	0.995 ~~0.997~~	$\frac{0.0317\ (2.5)}{(29.00)(71.75 + 460)}\left[\frac{(66 + 460)(12.67)}{(10.52)}\right]^2$	2.062
	AVERAGE	1.003		AVERAGE 2.048

(γ) Gamma = ratio W_t to D_t
Tol. = ±.01

$\Delta H@$ = orifice pressure differential that gives 0.75 cfm of air at 68°F and 29.92" Hg. Average $\Delta H@$ value between 1.59-2.09 is acceptable. In addition, the $\Delta H@$ must not vary by more than ±0.15 over the ΔH range of calibration of 0.5-2.50" H_2O.

READ AND UNDERSTOOD BY	DATE
Jay C. Yeager II	1-7-80